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Chapter 22

Impact of the design-build process on the construction and functionality of a large-scale live coral exhibit at the Houston Zoo: "Reef-building by design-build"

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ABSTRACT
In 2002, planning began for the construction of a large-scale live coral exhibit as part of a massive building renovation. An outside Project Manager was brought in to oversee and direct construction utilizing a "design-build" philosophy. During construction of the exhibit, several choices were made which had a large impact on the functionality and ergonomics of the final product. For example, alteration of the original overflow design resulted in under-exploitation of the main circulation pump and an increase in tank volume (without consideration of life support design) further compounded this issue. Other errors made were largely the result of a lack of communication with individuals who were familiar with the husbandry requirements of corals. Completion of the exhibit required modification of the existing structure and life support systems, particularly with respect to water flow. FRP grating was utilized as a framework to secure more than 1,800 kg of live rock and live sand, and "matured" water was used to accelerate biological cycling. Lessons gleaned from this project include the importance of open communication with contractors and the necessity for a well developed plan in the construction of a live coral exhibit. Other issues encountered during operation will be discussed.

INTRODUCTION

Although several texts have been published regarding the construction and design of live coral aquaria (Adey and Loveland, 1991; Delbeek and Sprung, 1994; Nilsen and Fossa, 1996; Delbeek and Sprung, 2005), they have been largely aimed towards smaller exhibits. While there is significant overlap between the needs of hobbyists and that of professional aquarists, the latter face some unique challenges. As advances in coral husbandry, aquaculture and technology accrue, public aquaria have begun to test the limits of size and complexity on their displays. The creation of larger exhibits requires stronger materials, larger pumps, more robust filtration and more raw material than that of the typical home aquarium.

Essentially, the bulk of information regarding the creation of larger coral displays has been transmitted via personal communications and conference presentations. In order for all aquarists to benefit from the successes and failures of others, this information needs to be compiled in an organized fashion that is easily accessible to all. Accounts regarding the construction of exhibits can be considered as "case studies" regarding what works well and what does not. The construction of a new live coral exhibit at the Houston Zoo provides insights on system design and aquascaping that may serve to help others undertaking similar projects.

METHODS AND MATERIALS

Concept and design

Due to the variables involved in the reconstruction of an existing building, a "design-build" philosophy was utilized in an effort to allow the project to progress more efficiently. Partial demolition was completed and construction

was able to proceed before the design was finalized. The flexibility afforded by controlling all aspects of construction was intended to minimize problems encountered during the build. Total Parks Management, who assumed ultimate authority and responsibility for the endeavor, provided project management.

The initial concept for the live coral exhibit featured a curved acrylic display panel measuring approximately 6.0 m in length. Internal dimensions, while not finalized, were to yield a volume of approximately 13,250 L. Based on this initial estimate, life support systems were designed by subcontractor TJP, while Curator George Brandy and Life Support Specialist Roy Drinnen selected equipment for the exhibit.

Construction and life support

Vaughn Construction carried out partial demolition of the building in early 2004. A decision was made by the Project Manager to extend the length of the tank by more than 2.5 m. The floor and bottom “lip” of the enclosure were fashioned of poured concrete. Options for the retaining wall included poured concrete, fiberglass lining and cinder block construction. Total Parks Management opted for cinder block construction, reinforced with poured concrete. Due to concerns expressed by the Aquarium and Life Support staff, the enclosure was buttressed by three vertical steel beams for extra support. Six penetrations were cut into the retaining wall in order to house 50.8 mm diameter influent pipes, with one additional penetration to accommodate a 152.4 mm diameter effluent line connected to a custom overflow box. Several layers of Sikagard 62 (Sika Corporation, United States) epoxy coating were applied to both the interior and exterior of the walls as a waterproofing agent. The same product was used to coat all steel structures in the vicinity of the tank after being thoroughly sand blasted.

Reynolds Polymer (Reynolds Polymer, Inc., United States) provided a curved acrylic viewing panel measuring 8.5 m long and 2 m high, with a thickness of 76 mm. Due to the dimensions of the panel, it was necessary to vertically bond two segments together. The bottom poured concrete lip as well as overhead steel bracings provided support (Figure 1). Installation of major life support components was carried out by Graco Mechanical, Inc. Circulation was provided by a Fybroc Series 2530 pump (Metro Corporation: Fybroc Division, United States). An RK2 model RK75PE (RK2 Systems, United States) was employed for foam fractionation, fed by a WhisperFlo WFK – 4 pump (Pentair, Inc., United States). An identical pump was utilized to power a sidestream loop containing a 5 HP Chiller (AquaLogic, Inc., United States) as well as a small volume JF80 canister filter (AquaLogic, Inc., United States) for adsorbent media. All pumps received effluent from a

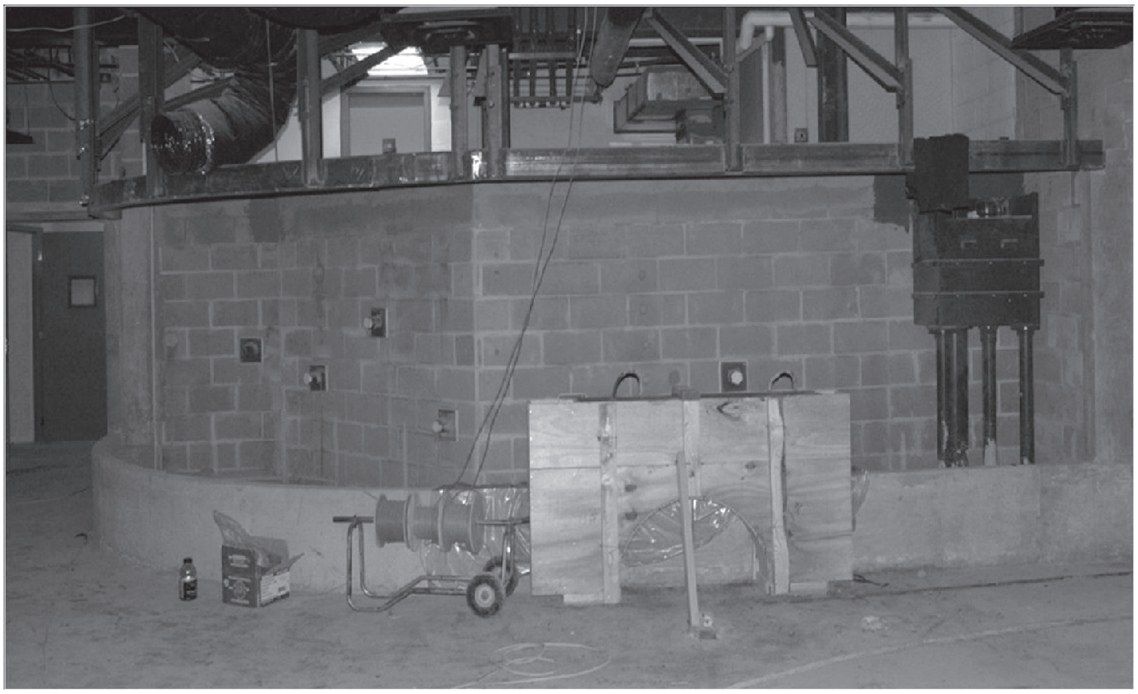

Figure 1: Basic structure of exhibit and location of influent and effluent piping (photo by George Brandy)

custom sump measuring 1.17 m x 1.60 m x 2.13 m (AquaLogic, Inc., United States) that was fed via corner overflow.

Aquascaping

Due to the narrow profile of the tank in relation to its height (as little as 1 m in many areas), large horizontal structures were not plausible in most regions. Stacking a thin layer of live rock to a height of 1.5 m would have required a wide base, and materials such as cinder blocks would have taken up precious space. A recent endeavor at the Waikiki Aquarium had utilized Fiberglass Reinforced Plastic (FRP) grating as a framework for reef structure (Delbeek, J.C., pers. com.) quite successfully. Several sheets of 3.81 cm x 3.81 cm FRP grating (SeaSafe, United States) were obtained and a general structure mapped out. Engineered Processes, Inc. was given these templates as a guide for construction as well as the responsibility of securing the structure to the retaining wall. Vertical sections were secured to the retaining wall with standard FRP brackets (Engineered Processes, Inc., United States) and stainless steel bolts, and additional strips of FRP grating were used as spacers at the top and bottom of the structure to allow flow behind the framework

(Figure 2). Horizontal structures were fastened to the vertical elements with FRP brackets and fiberglass bolts sandwiched between fiberglass nuts. In addition, an 18 cm tall plenum platform was formed with the same material in order to reduce the depth of the substrate and facilitate denitrification. Adjustable threaded fiberglass risers (Figure 3) were used to support the plenum structure (Engineered Processes, Inc., United States). Silicon was used to adhere 1000 µm screening to the filter plate.

The framework was then disassembled and Aquarium staff then made necessary modifications. Cut ends were sealed with Styrene resin. Influent projections were outfitted with 5.08 cm diameter PVC “tees” and flexible pipes in an effort to redirect and maximize water flow. For aesthetic purposes, 63.5 mm black acrylic sheets (Marine Plastics, United States) were attached to exposed cinder block surfaces with silicon (732 Multi-Purpose Sealant, Dow Corning, United States).

Water test and operation

After the FRP grating was reinserted (Figure 4), the tank was filled with freshwater and LSS operation was examined. It was found that raising the overflow box, combined with a very circuitous plumbing path, had resulted in a lack of ability to handle the total flow provided by the main pump, so a bypass loop was utilized in order to match influent and effluent rates. All other elements functioned properly during the test. Table salt was added at a concentration of 60 ppt in an effort to leach any possible contaminants contained in the FRP. Leaching was carried out over a period of 20 days.

Figure 2: Showing FRP brackets used to secure FRP grating to wall.

Figure 3: The placement of adjustable risers used for elevating plenum and other structures in the exhibit (photo by George Brandy)

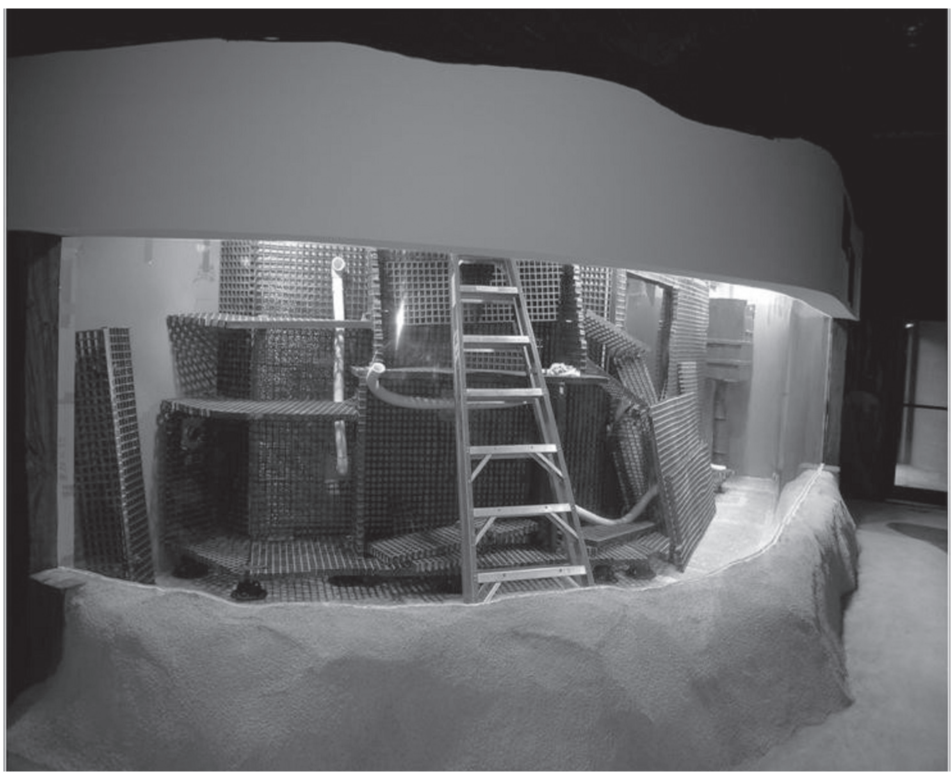

Figure 4: The basic structure of the exhibit, as well as modification of influent penetrations to disperse flow (photo by George Brandy)

Aquascaping

A shipment of 1,818 kg of Fiji live rock was acquired through Eric Koch (Reef Savers, United States). Due to lack of holding space, the rock was cured at the Moody Gardens quarantine facility in Galveston, TX for several months. The tank was drained and the majority of the rocks were secured to the framework with nylon cable ties (Catamount 5 mm – 15 mm, Thomas & Betts, United States). Rocks that were lacking natural holes or fissures were modified with a hammer drill to create suitable openings. Aquarium staff spent three days hanging rocks to complete the exhibit, with plastic covering the exhibit overnight in order to maintain high humidity. Flexible PVC pipes used to provide influent to the tank were hidden within the rockwork and were also attached to the framework with cable ties. After the rockwork was secured, 1,818 kg of sugar-sized live sand were obtained from Reef Savers' holding systems. Several hundred kilograms of Fiji Pink Special Grade aragonite (Caribsea, United States) was mixed in to provide heterogeneity for infauna, and the resultant depth averaged approximately 10 cm. Aged water was also taken from the Reef Savers' systems, with a total volume of 13,200 L transported to the zoo by Texas Brine Company. The remaining 5,700 L was mixed at the Houston Zoo. Live substrata and aged water were used in hopes of speeding the biological cycling process.

RESULTS

The Carruth Natural Encounters Building was opened to the public in March 2005. Nitrogen levels were monitored in the reef display for the first six weeks, with negligible accretion of NH_3, NO_2^- or NO_3^- (Figure 5). Herbivorous fishes, gastropods, echinoderms and decapods were added in mid-April in an effort to control potential nuisance algae and corals were introduced in August, with a heavy emphasis on scleratinian species. Stocking of fishes and invertebrates continued through early 2006. Several powerheads (TAAM, Inc., United States) were installed to improve water flow, but stagnation was still an issue, particularly on the long arm of the tank. An additional WhisperFlo WFK – 4 pump (Pentair, United States) was incorporated into the system by using one of the influent penetrations. Multidirectional flow was accomplished with a manifold consisting of seven 19.05 mm diameter PVC pipes terminating in short sections of flexible PVC, which were hidden in the rockwork. Several Tunze Turbelle Stream kits (TUNZE, Germany) were also installed to randomize and improve water flow. Seven of fourteen contractor-installed 400 W metal halide pendants (HP8MOG, PFO lighting, United States) driven by electronic ballasts (400MH, IceCap, Inc., United States) were replaced by 1000 W metal halide pendants (Illuminator hood, PFO Lighting, Inc., United States) driven by M83 pulse start ballasts

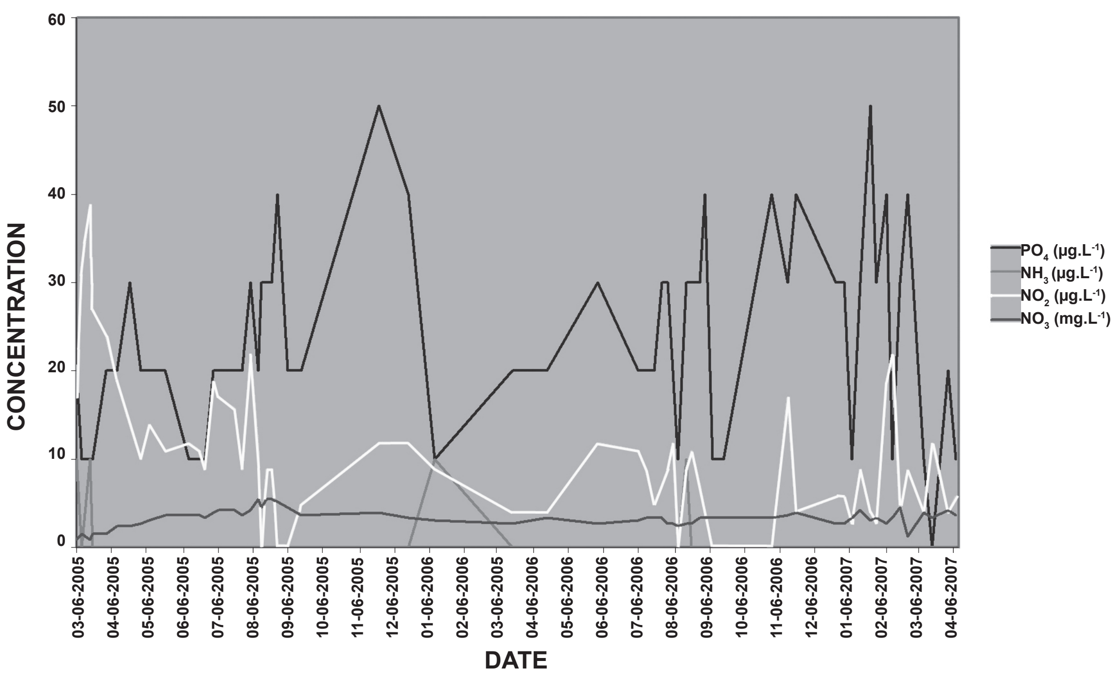

Figure 5: Nitrogen and phosphate concentrations in the exhibit.

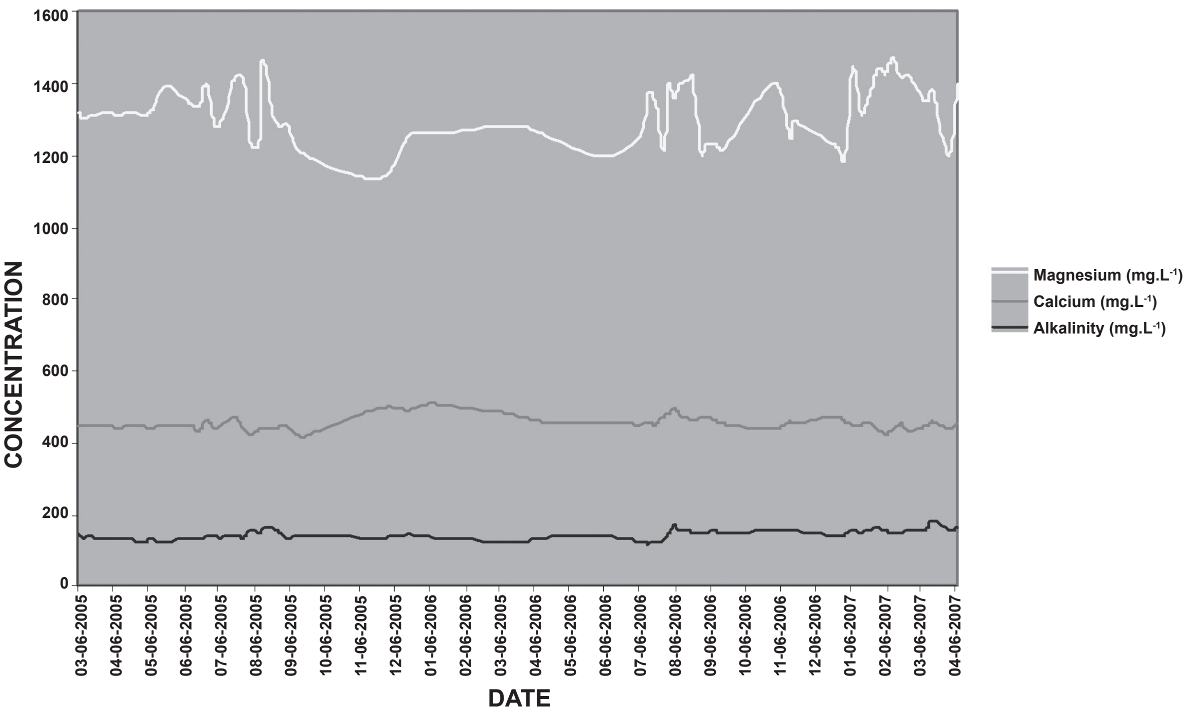

Figure 6. Development of alkalinity, calcium and magnesium concentrations

(model discontinued, PFO Lighting, Inc., United States). Bulbs utilized in the 400 W fixtures (Mogul 400 W 20,000 K, XM, United States) and 1000 W fixtures (UHI-S1000AQ/10, Ushio, Germany) combined to create a pleasant, crisp blue spectrum. Photoperiod was controlled by the ET70815CR (InterMatic, United States) timer, which offered astronomical clock settings. Calcium and alkalinity levels were supported by a professional CR250 calcium reactor (Schuran, Germany).

DISCUSSION

By far, the largest impact the design-build process had on the functionality of the tank involved the 40 % increase in tank volume. Life support systems and equipment were designed and selected for a much smaller exhibit than the finished product. The main pump's output was restricted to 80 % of its full capacity, owing largely to the (necessarily) circuitous plumbing path and the modifications made to the skimmer box. Turnover, and water flow in general, suffered greatly because of this design modification. Additionally, only two penetrations were cut into the lengthened portion of the exhibit; further compounding flow problems in that region. Modifying one of the original outlets for use as a supply line for the additional circulation pump resulted in only five influent paths into the tank. Replacing half of the 400 W fixtures represented an unnecessary cost. Many of these issues could have been avoided by keeping communication channels between design team, contractor and client open and not understanding the lighting and flow requirements of corals resulted in deficiencies in the design. The choice of cinder blocks for construction of the retaining wall may eventually prove to be a dubious one.

Protective coatings used on metal structures surrounding the tank were recoated with Carboline Carboguard 691 (Carboline Company, United States) by the Pascoe Group in 2006, replacing the original Sika 62 coating which had failed, allowing rust to develop in several areas. Sika 62 applied to the outside of the retaining wall began to chip slightly near the floor, due to poor drainage in the room.

After 14 months of operation, nylon cable ties began to break, and continue to do so occasionally; ties wider than 76 mm fared better. Although failure of the cable ties may have been due simply to improper utilization, alternative methods of securing rock should be considered in future endeavors. Epoxies, cyanoacrylate gel and nylon screws used to attach corals fared better.

Issues also arose with the black acrylic paneling used to cover bare walls in the exhibit. Over time, the material began to warp and peel away from the cinderblock. A more durable or easily

replaceable covering would be desirable e.g. Korogard PVC wall covering material.

CONCLUSION AND FUTURE DIRECTION

Overall, the exhibit is a success. Coral growth and coloration is good, and water chemistry values fall within accepted ranges (Figures 5 and 6) for scleractinian-dominated aquaria. Rapid coral growth in the exhibit is exacerbating the deficiencies in flow. Unobtrusive sources of additional non-laminar flow are being sought to rectify the situation. Propellor-driven units may prove to be the solution (Joe Yaiullo, Atlantis Aquarium, pers. com.). Over time, it has become clear that the calcium reactor alone is not adequate to support desired alkalinity and calcium levels. Both calcium hydroxide and two-part additives are currently necessary to maintain elevated levels. The addition of a second chamber or larger reactor is likely in the future, to alleviate the dependence on chemical additions. Unused astronomical functions of the Intermatic timer may be implemented to provide seasonal photoperiod changes as well as lunar simulation.

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Fossa S.A. and A.J. Nilsen, 1996. The Modern Coral Reef Aquarium, Volume 1, 1st edn. Birgit Schmettkamp Verlag, Bornheim, Germany. 367 pp.

PERSONAL COMMUNICATIONS

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Yaiullo, J., 2007. Atlantis Aquarium, New York, USA

APPENDIX I: Aquarium Passport live coral exhibit Houston Zoo

Tank name	Natural Encounters Coral Reef Exhibit
Location	Carruth Natural Encounters Building at The Houston Zoo, Inc. (Houston,TX)
Opening date	March 2005

INFRASTRUCTURE / PHYSICAL DESCRIPTION

Volume	Approximately 19,000 L
Surface area	Approximately 9.0 m^2
Depth	Approximately 2.25 m

LIGHT CONDITIONS

General	Artificial metal halide lighting: 7 x 1,000 W (10,000 K USHIO), 7 x 400 W (20,000 K XM)		
Hours of illumination	13 h ramped		
Daily max PAR	<u>0.5 to 1 m depth</u>	<u>2.5 m depth</u>	<u>4.0 m depth</u>
	NA	NA	NA
Total daily integrated daylight	<u>0.5 to 1 m depth</u>	<u>2.5 m depth</u>	<u>4.0 m depth</u>
	NA	NA	NA

FILTRATION (external)

Protein skimmers	RK75PE
Ozone injection	NA
Sand filters	NA
Vacuum by divers	~1 h per month; substrate is stirred 3 times per week during maintenance

FILTRATION (internal)

Live-rocks	1818 kg of Fiji live rock , with an additional 100 kg of Totoka rock added subsequently
Substrate	1818 kg of live sugar-sized sand initially added to tank; more than 100 kg mixed grade aragonite added subsequently

WATER MOVEMENT / CIRCULATION

External pumps	Fybroc Series 2530 pump providing laminar flow via 5 x 50.8 mm penetrations (with restrictions, approximately. WhisperFlo WFK – 4 pump providing laminar flow via 7 x 19 mm flex PVC Maximium of 50,000 $L.h^{-1}$
Submerged pumps	2 x RIO 3100 and 7 x TUNZE 6200 Maximum of 150,000 $L.h^{-1}$
Wave machine	TUNZE Turbelle Controller varies output from 80 % to 100 %
Total flow	Maximium of 200,000 $L.h^{-1}$
Flow in bottom 1 m	NA
Turn around rate [2]	22 minutes based on main external pump output
Filtration flow	Up to 50,000 $L.h^{-1}$

WATER CHANGES

Type of system	Closed system with minimal water changes performed on the order of approximately 5% per month	
Source of "new" salt-water	Hawaiian Marine Professional Salt Mix dissolved in RODI water	
Characteristics of "new" saltwater	Calcium: 430 mg $Ca^{2+}.L^{-1}$	Nutrients
	Magnesium: 1250 $mg.L^{-1}$	Nitrate: 0 mg $NO_3^-.L^{-1}$
	Salinity: 33-37 ppt	Nitrite: 0 mg $NO_2^-.L^{-1}$

APPENDIX I (continued): Aquarium Passport live coral exhibit Houston Zoo

Characteristics of "new" saltwater	Alkalinity : 2,5 mEq.L^{-1} Phospate: 0.02 mg $PO_4^{3-}.L^{-1}$ Temperature: 22-28 ºC pH: 8.1
Rate of water replacement	5% exchanged per month on average

FEEDING REGIME

Dead food

Diet Item (measure)	Sun	Mon	Tues	Wed	Thu	Fri	Sa
Artemia eggs (grams)	5	5	5	5	5	5	5
Beta-Meal (grams)				36			
Bloodworms (grams)	15	15	15	15	15	15	15
Clams (grams)	7.1	7.1	7.1	7.1	7.1	7.1	7.1
Cyclopeeze (grams)*						10	
Gel Diet (grams) Herbivore	10						
Gel Diet (grams) Omnivore					10		
Krill (grams)	15	15	15	15	15	15	15
Mysids (grams)	15	15	15	15	15	15	15
Nauplii (tsp.)				3			3
Nori (sheets)	0.5	1.5	0.5	1.5	0.5	1.5	0.5
Pellets-Small (grams)	4	4	4	4	4	4	4
Selco (grams)	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Shrimp (grams)	42			42		42	
Spirulina (grams)	1.5	1.5	1.5	1.5	1.5	1.5	1.5

Live food

Diet Item (measure)	Sun	Mon	Tues	Wed	Thu	Fri	Sa
Artemia (tsp.)	3		3		3		

WATER QUALITY

Salinity	33 to 36 ppt(uncontrolled natural variations)	
Temperature	25 to 29 °C with natural daily variations of ~1 °C	
pH	7.9 to 8.2	
Redox (mV)	NA	
Dissolved Oxygen	NA	
Nutrients	Nitrate (mg NO_3^-):	< 5.0 mg.L^{-1}
	Nitrite (mg NO_2^-):	< 0.020 mg.L^{-1}
	Phosphate (mg PO_4^{3-}):	0.01 to 0.05 mg.L^{-1}
	Dissolved Organic Nitrogen (mg DON-N.L^{-1}):	NA
	Dissolved Organic Phosphate (mg DOP-P.L^{-1}):	NA

CHEMICAL ADDITIONS

Calcium	360 g $CaOH_2$ added weekly
Alkalinity	Occasionally supplemented with ESV Super Buffer dKH
Trace elements	300 mL $SrCl_2$ added weekly

1 Calculated from continuous record at 4m depth, integrated between 6 am and 6 pm, and averaged over many months of data at several locations in the tank.

2 Time to move every water particle at least once through the circulation and filtration systems.

APPENDIX II: Species in the exhibit and their relative abundances

FISHES

0.0.1	*Acanthurus leucosternon*
0.0.1	*Acanthurus tennenti*
0.0.18	*Amphiprion ocellaris*
1.2	*Bodianus bimaculatus*
0.0.1	*Chelmon rostratus*
1.2.0	*Cirrhitichthys falco*
0.0.7	*Dascyllus aruanus*
0.0.2	*Ecsesius bicolor*
0.4.0	*Genicanthus melanospilos*
1.0.0	*Naso brevirostris*
1.0.4	*Naso vlamingi*
0.0.5	*Paracanthurus hepatus*
0.0.4	*Pseudanthias hutchii*
2.5.0	*Pseudanthias pleurotaenia*
2.3.0	*Pseudanthias squamapinnis*
1.0.8	*Ptereleotris zebra*
0.0.1	*Siganus corallinus*
0.0.1	*Siganus magnificus*
0.0.1	*Siganus vulpinus*
3.3.1	*Sphaeramia nematoptera*
1.1.0	*Synchiropus ocellatus*
0.0.3	*Zebrasoma velliferum*

MOTILE INVERTEBRATES

0.0.50	*Astrea* sp.
0.0.100	*Calcinus elegans*
0.0.4	*Colochirus quadraingularis*
0.0.4	*Colochirus robustus*
0.0.20	*Cypraea moneta*
0.0.3	*Diadema setasum*
0.0.2	*Entamacea quadricolor*
0.0.1	*Hippopus hippopus*
0.0.4	*Holothuria* sp.
0.0.3	*Mespilia globulus*
0.0.10	*Mithrax* spp.
0.0.33	*Nassarius* sp.
0.0.100	*Nerites sp.*
0.0.6	*Ophioderma* sp.
0.0.12	*Percnon* sp.
0.0.10	*Stichopus* sp.
0.0.3	*Strombus gigas*
0.0.5	*Tridacna crocea*
0.0.1	*Tridacna maxima*
0.0.200	*Trochus* sp.

SESSILE INVERTEBRATES

0.0.43	*Acropora* spp.
0.0.1	*Blastomussa* sp.
0.0.21	*Caulastrea* sp.
0.0.2	*Caulastrea* sp.
0.0.1	*Cycloseris* sp.
0.0.2	*Echinophyllia*
0.0.3	*Entamacea quadricolor*
0.0.2	*Euphyllia ancora*
0.0.10	*Euphyllia glabrescens*
0.0.10	*Euphyllia paradivisa*
0.0.2	*Euphyllia paradivisa*
0.0.1	*Euphyllia paradivisa*
0.0.4	*Favia/Favites* spp.
0.0.1	*Fungia* sp.
0.0.6	*Galaxea* sp.
0.0.1	*Goniastrea* sp.
0.0.1	*Heliofungia* sp.
0.0.2	*Heliopora caerulea*
0.0.10	*Hydnophora* sp.
0.0.1	*Hydnophora* sp.
0.0.4	*Klyxum* sp.
0.0.1	*Lobophyllia* sp.
0.0.1	*Merulina* sp.
0.0.31	*Montipora* sp.
0.0.20	*Montipora* sp.
0.0.3	*Montipora* sp.
0.0.5	*Montipora* sp.
0.0.1	*Montipora* sp.
0.0.1	*Montipora* sp.
0.0.5	*Montipora* sp.
0.0.1	*Montipora* sp.
0.0.1	*Pachyclavularia violacea*
0.0.4	*Palythoa* sp.
0.0.1	*Palythoa* sp.
0.0.4	*Pavona* sp.
0.0.1	*Pectinia* sp.
0.0.1	*Pectinia* sp.
0.0.5	*Platygyra* spp.
0.0.1	*Plerogyra sinuosa*
0.0.4	*Pocillopora eydouxi*
0.0.2	*Pocillopora* sp.
0.0.3	*Pocillopora* sp.
0.0.6	*Rhodactis* sp.
0.0.4	*Sarcophyton elegans*
0.0.4	*Sarcophyton* spp.
0.0.1	*Seriatopora* sp.
0.0.9	*Sinularia* sp.
0.0.2	*Stylophora* sp.
0.0.1	*Stylophora* sp.
0.0.4	*Trachyphyllia* sp.
0.0.5	*Turbinaria mesenteria*
0.0.2	*Turbinaria peltata*
0.0.2	*Turbinaria reiniformis*
0.0.9	*Zoanthus* spp.